

## **Summary of Major Points – Testimony of James W. Hurrell – March 7, 2007**

### **Are global temperatures increasing?**

The iconic statement from the observations chapter of the IPCC Fourth Assessment Report (AR4) is the “warming of the climate system is unequivocal.” This is based on an increasing number of many independent observations that give a consistent picture of a warming world. A limited sample of the evidence includes:

- Average global surface temperature has warmed over the last 50 years, with a greater rate of 0.17°C (0.3°F) per decade since 1979.
- Global average sea surface temperatures have warmed 0.35°C (0.6°F) since 1979.
- Global sea level has risen at a rate of 0.31 cm per year since 1993.
- Arctic summer sea-ice extents and Northern Hemisphere snow cover have decreased, and permafrost layer temperatures have increased since the 1980s.
- The number of heat waves globally has increased, and there have been widespread increases in the numbers of warm nights. Frost days are rarer.

### **To what extent is the increase attributable to greenhouse gas emissions from human activity as opposed to natural variability or other causes?**

Climate model simulations have now reliably shown that global surface warming of recent decades is a response to the increased concentrations of greenhouse gases and sulfate aerosols in the atmosphere. When the models are run with natural forcing changes alone, they fail to capture the large increase in global surface temperatures over the past 25 years. Moreover, the spatial pattern of observed warming, which includes greater warming over land than over the ocean, is only simulated by models that include anthropogenic forcing. Discernible human influences now extend to other aspects of the climate as well, including ocean warming, continental-average temperatures, temperature extremes, and changes in precipitation.

### **How will future global temperatures be affected by greenhouse gas emissions from human activity?**

The ability of climate models to simulate the past climate record gives us increased confidence in simulations of the future. Some major conclusions from the IPCC AR4 are:

- The rate of the projected global warming is near 0.2°C per decade through 2030 regardless of the emission scenario. Likewise, warming and significant changes in precipitation will continue over each inhabited continent.
- By the middle of the 21<sup>st</sup> Century the choice of scenario becomes more important.
- Continued greenhouse gas emissions at or above current rates would very likely induce many changes in climate much larger than those observed to date.
- Snow cover and sea ice coverage are projected to contract.
- It is very likely that hot extremes, heat waves, and heavy precipitation events will continue to become more frequent.
- Even if greenhouse gas concentrations were to be stabilized, anthropogenic warming and sea level will continue for centuries.

Statement of  
James W. Hurrell, Ph. D. <sup>\*</sup>  
Director, Climate and Global Dynamics Division  
National Center for Atmospheric Research <sup>\*\*</sup>

Before the  
U.S. House of Representatives Subcommittee on Energy and Air Quality  
Committee on Energy and Commerce  
7 March 2007

Hearing on  
*Climate Change: Are Greenhouse Gas Emissions from Human Activities Contributing to  
a Warming of the Planet?*

---

<sup>\*</sup> Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author and do not necessarily reflect those of the National Science Foundation.

<sup>\*\*</sup> The National Center for Atmospheric Research (NCAR) is sponsored by the National Science Foundation.

## **Introduction**

I thank Chairman Boucher, Ranking Member Hastert, and the other Members of the Subcommittee for the opportunity to speak with you today on observed and likely future changes in climate and the contribution from human activity to those changes. My name is James W. Hurrell. I am a Senior Scientist at the National Center for Atmospheric Research in Boulder, Colorado, where I am also the Director of the Climate and Global Dynamics Division. My personal research has centered on empirical and modeling studies and diagnostic analyses to better understand climate, climate variability and climate change. I have authored or co-authored nearly 70 peer-reviewed scientific journal articles and book chapters, as well as dozens of other planning documents and workshop papers. I have given more than 75 invited talks worldwide, as well as many contributed presentations at national and international conferences on climate. I have also convened over one dozen national and international workshops, and I have served on several national and international science-planning efforts. Currently, I am extensively involved in the World Climate Research Programme (WCRP) on Climate Variability and Predictability (CLIVAR). I am the former co-chair of Scientific Steering Committee of U.S. CLIVAR, and I am the current co-chair of the Scientific Steering Group of International CLIVAR. I have also been involved in the assessment activities of the Intergovernmental Panel on Climate Change (IPCC) as a contributing author to chapters in both the Third and Fourth Assessment Reports, and I have served on several National Research Council (NRC) panels. I was a lead author on the U.S. Climate Change Science Program's (CCSP) Synthesis and Assessment Product on Temperature Trends in the

Lower Atmosphere, and I am currently serving on a NRC committee tasked to provide strategic advice to the CCSP.

Throughout this testimony I will refer extensively to the IPCC. Briefly, the IPCC is convened by the United Nations jointly under the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO). Its mandate is to provide policymakers with an objective assessment of the scientific and technical information available about climate change, its environmental and socio-economic impacts, and possible response options. The IPCC reports on the science of global climate change and the effects of human activities on climate. It does not do or manage research. It has provided policymakers assessment reports since 1990, and the Fourth Assessment Report (AR4) is being released this year. Each IPCC report reviews all the published literature over the previous 5 years or so, and assesses the state of knowledge, while trying to reconcile disparate claims, resolve discrepancies and document uncertainties. The IPCC assessments are produced through a very open and inclusive process. The volunteer authorship of the AR4 in Working Group I (WGI) includes 152 lead authors and over 400 contributing authors from over 130 countries. In addition, there were more than 30,000 comments from over 600 reviewers, as well as formal coordinated reviews by dozens of world governments, including the U.S. All review comments must be addressed, and review editors are in place for each chapter of the report to ensure that this is done in a satisfactory and appropriate manner.

In today's testimony I have been asked to address three specific questions, all related to surface temperature. My answers to each will draw upon the same literature assessed by IPCC WGI, and they will reference several of the major conclusions highlighted in the

WGI Summary for Policymakers (SPM) released 2 February, 2007 in Paris, France. The WGI is tasked with appraising how and why the climate has changed, including the role of human activity, and it assesses projections of future climate change based upon various emission scenarios. The other two IPCC Working Groups deal with impacts of climate change, vulnerability, and options for adaptation and mitigation, including possible policy options.

### **Are global temperatures increasing?**

Analyses of instrumental measurements of surface temperature averaged across the globe reveal a warming rate of about 0.17°C (0.3°F) per decade since 1979, and 11 of the last 12 years rank among the 12 warmest years since 1850 (1996 being the exception). Since the release of the IPCC Third Assessment Report (TAR) in 2001, the four years of 2002-2005 were the warmest in the historical record behind only 1998 (when a strong El Niño event enhanced the warming). The 2006 average global surface temperature is near the average of the past five years, and it was the warmest on record over the United States. Global land regions have warmed the most (0.7°C or 1.3°F) since 1979, with the greatest warming in the boreal winter and spring months over the Northern Hemisphere (NH) continents. The updated 100-year linear trend (1906–2005) of 0.74°C (1.4°F) is therefore larger than the corresponding trend for 1901-2000 given in the TAR of 0.6°C. Over the last 50 years, the rate of warming is nearly double that of the 100-year trend.

There is a very high degree of confidence in the global surface temperature values and the change estimates. Independent teams of scientists have laboriously analyzed and improved the historical surface temperature data, and trend estimates from the different

groups are very similar over all time periods. The maximum difference, for instance, among three independent estimates of global surface temperature change since 1979 is 0.01°C per decade. Spatial coverage has improved, and daily temperature data for an increasing number of land stations have also become available, allowing more detailed assessments of extremes, as well as potential urban influences on both large-scale temperature averages and microclimate. It is well documented, for instance, that urban heat island effects are real, but very local, and they have been accounted for in the analyses: the urban heat island influence on continental, hemispheric and global average trends is at least an order of magnitude smaller than decadal and longer timescale trends.

There is no urban heat bias in the sea surface temperature (SST) record. Over the global oceans, surface temperatures have warmed 0.35°C (0.6°F) since 1979, and the warming is strongly evident at all latitudes over each of the ocean basins. Moreover, the warming is evident at depth as well. Since 1961, for instance, the average temperature of global ocean water has increased from the surface to depths of at least 3000 m, indicating that the ocean is absorbing most of the heat being added to the climate system.

The ocean warming causes seawater to expand and, thus, contributes to sea level rise. Instrumental measurements of sea level indicate that the global average has increased 0.18 cm per year since 1961, with a faster rate of 0.31 cm per year since 1993. Over the last century, global sea level rose approximately 17 cm. While much (60%) of this rise is due to thermal expansion, there are other sources of increased ocean volume, including melting from glaciers and ice caps. New satellite data records over the past decade also indicate that mass losses from the ice sheets of Greenland and Antarctica have also likely contributed to global sea level rise, but only recently. In addition, flow speed has recently

increased for some Greenland and Antarctic outlet glaciers, which drain ice from the interior. Notably, the observation of consistent sea level rise is powerful evidence that the globe has warmed: there is no other explanation.

The aforementioned changes in global average surface temperature, SST and sea level do not imply, however, that changes are uniform around the globe. There are notable regional and seasonal variations, especially over relatively short time periods (year-to-year and even decade-to-decade). Regional differences in SST change arise, for instance, from natural variability and other factors. One example is the very strong warming of the central and eastern tropical Pacific Ocean that occurs during El Niño events. These events also produce regional ocean cooling over portions of the subtropics and the tropical western Pacific. Over the Atlantic, the average basin-wide warming is imposed on top of strong, natural variability on multi-decadal time scales. The level of natural variability, in contrast, is relatively small over the tropical Indian Ocean, where the surface warming has been steady and large over recent decades. These important differences in regional rates of surface ocean warming also affect the atmospheric circulation, producing changes in the atmospheric flow so that some regions warm more than others, while other regions cool, especially over periods of years or even decades. Yet, numerous changes in regional climate have been observed that are consistent with longer-term surface warming.

Snow cover has decreased in many NH regions, particularly in the spring season, and this is consistent with greater increases in spring than autumn surface temperatures in middle latitude regions. Sea-ice extents have decreased in the Arctic, particularly in the spring and summer seasons (7.4% per decade decrease since 1978), and this is consistent

with the fact that the average annual Arctic temperature has increased at almost twice the global average rate. Arctic sea-ice extents were at record low values in 2005, which was also the warmest year since records began in 1850 for the Arctic north of 65°N. There have also been decreases in sea-ice thickness. Temperatures at the top of the permafrost layer in the Arctic have increased since the 1980s (up to 3°C locally), and the maximum area covered by seasonally frozen ground has decreased by about 7% in the NH since 1900, with an even greater decrease in the boreal spring. There has been a reduction of about two weeks in the annual duration of northern lake and river ice cover.

In contrast to the Arctic, there is no significant trend in Antarctic sea ice since the end of the 1970s, which is consistent with the lack of a trend in surface temperature south of 65°S over that period. However, the warming of the Peninsula region since the early 1950s is one the largest and the most consistent warming signals observed anywhere in the world. Large reductions in sea-ice have occurred to the west in the Bellingshausen Sea, and on the eastern side of Peninsula, and large reductions in the size of Larsen Ice shelf have occurred.

For any change in mean temperature, there is likely to be an amplified change in extremes. Extreme events, such as heat waves, are exceedingly important to both natural systems and human systems and infrastructure. We are adapted to a range of natural weather variations, but it is the extremes of weather and climate that exceed tolerances. Widespread changes in temperature extremes have been observed over the last 50 years. In particular, the number of heat waves globally has increased, and there have been widespread increases in the numbers of warm nights. Cold days, cold nights and days with frost have become rarer.



Long-term changes in upper-air temperatures are less certain than those at the surface. This is because of sparser spatial coverage and fewer observations overall, significant and frequent changes in instrumentation, and difficulties adjusting and merging different satellite records, among other factors that make the creation of long-term, homogenous upper-air temperature records difficult. Nevertheless, available measurements indicate global average warming in both the lower and the middle troposphere that is broadly consistent with the observed surface temperature change, largely reconciling a discrepancy that was noted in the TAR. A warmer atmosphere can also hold more water vapor, and indeed the average atmospheric water vapor content has increased since at least the 1980s over both land and ocean. For example, total column water vapor has increased over the global oceans by 1.2% per decade since 1988, consistent in pattern and amount with observed changes in SST and a fairly constant relative humidity. Increases in water vapor also mean that there is a greater supply of atmospheric moisture to storms; in fact, increases in moderate to heavy precipitation events have been observed over most land areas in recent decades.

Finally, paleoclimate data put the instrumental record into a much longer-term perspective. Based on reconstructions of temperature from proxy data, like tree rings, boreholes and ice cores, average NH temperatures over the last 50 years were very likely<sup>1</sup> higher than any other 50-year period in the last 500 years, and they were likely the highest in the past 1,300 years. These conclusions, articulated in the IPCC AR4, are also consistent with the principal findings of an independent study by the NRC in 2006. The task of the NRC committee, which was formed in response to a Congressional request,

---

<sup>1</sup> The IPCC AR4 defines the term “very likely” as the likelihood of a result exceeding 90%, and the term “likely” as exceeding 66%.

was to assess the state of scientific efforts to reconstruct surface temperature records for the Earth over approximately the last 2,000 years.

In summary, there are an increasing number of many independent observations that give a consistent picture of a warming world. Such multiple lines of evidence, the physical consistency among them, and the consistency of findings among multiple, independent analyses, form the basis for the iconic phrase of the observations chapter in the AR4 assessment: namely, that the “warming of the climate system is unequivocal”.

**If global temperatures are increasing, to what extent is the increase attributable to greenhouse gas emissions from human activity as opposed to natural variability or other causes?**

The IPCC has concluded that most of the observed temperature increase is “very likely” due to human activity. This conclusion is based on studies that assess the causes of climate change, first considering all the possible agents of climate change (forcings), both natural and from human activities. The capability of climate models to simulate the past climate is also assessed, given both the observations and estimates of past forcings, and the climate changes. Given good replications of the past, the forcings can be inserted one by one to disassemble their effects and allow attribution of the observed climate change to the different forcings.

Therefore, climate models are a key tool to evaluate the role of various forcings in producing the observed changes in global temperature. The best climate models encapsulate the current understanding of the physical processes involved in the climate system, the interactions, and the performance of the system as a whole. They have been

extensively tested and evaluated using observations. They are exceedingly useful instruments for carrying out numerical climate experiments, but they are not perfect, and some models are better than others. Uncertainties arise from shortcomings in our understanding of climate processes operating in the atmosphere, ocean, land and cryosphere, and how to best represent those processes in models. Yet, in spite of these uncertainties, today's best climate models are now able to reproduce the climate of the past century, and simulations of the evolution of global surface temperature over the past millennium are consistent with paleoclimate reconstructions.

As a result, climate modelers are able to test the role of various forcings in producing observed changes in climate, for instance over the past century. Forcings imposed on the climate system can be natural in origin, such as changes in solar luminosity or volcanic eruptions, the latter periodically adding considerable amounts of aerosol to the upper atmosphere for up to two years. Human activities also increase aerosol concentrations in the atmosphere, mainly through the injection of sulfur dioxide from power stations and through biomass burning. A direct effect of sulfate aerosols (small milky white particles readily seen from airplane windows) is the reflection of a fraction of solar radiation back to space, which tends to cool the Earth's surface. Other aerosols (like soot) directly absorb solar radiation leading to local heating of the atmosphere, and some absorb and emit infrared radiation. A further influence of aerosols is that many act as nuclei on which cloud droplets condense, affecting the number and size of droplets in a cloud and hence altering the reflection and the absorption of solar radiation by the cloud. The precise nature of aerosol/cloud interactions and how they interact with the water cycle remains a major uncertainty in our understanding of climate processes. Because man-

made aerosols are mostly introduced near the Earth's surface, they can be washed out of the atmosphere by rain. They therefore typically remain in the atmosphere for only a few days, and they tend to be concentrated near their sources such as industrial regions. Therefore, they affect climate with a very strong regional pattern and usually produce cooling.

In contrast, greenhouse gases such as carbon dioxide and methane are not washed out, so they have lifetimes of decades or longer. As a result, with continued emissions, they build up over time, as has been observed. Greenhouse gas concentrations in the atmosphere have increased markedly as a result of human activities since 1750, and they are now higher than at any time in at least the last 650,000 years. It took at least 10,000 years from the end of the last ice age for levels of carbon dioxide to increase 100 parts per million (ppm) by volume to 280 ppm, but that same increase has occurred over only the past 150 years to current values near 380 ppm. About half of that increase has occurred over the last 35 years, owing mainly to combustion of fossil fuels and changes in land use, and the carbon dioxide concentration growth-rate was larger during the last decade than it has been since the beginning of continuous direct measurements in the late 1950s. In the absence of controls, future projections are that the rate of increase in carbon dioxide amount may accelerate, and concentrations could double from pre-industrial values within the next 50 to 100 years.

Methane is the second most important anthropogenic greenhouse gas. Owing predominantly to agriculture and fossil fuel use, the global atmospheric concentration of methane has increased from a pre-industrial value of 715 part per billion (ppb) by volume to 1774 ppb in 2005, although growth rates have declined since the early 1990s,

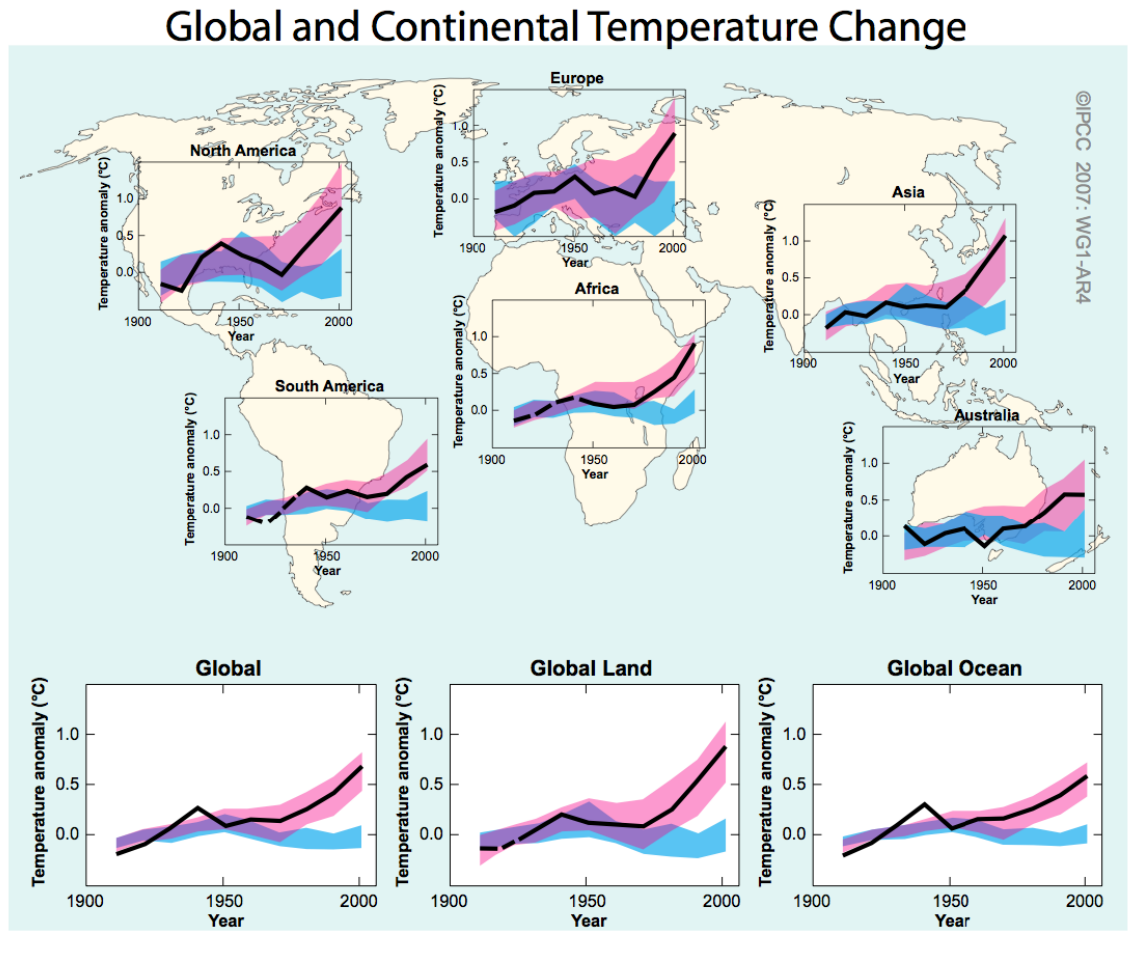
consistent with total emissions (sum of natural and anthropogenic sources) being nearly constant over this period. Global nitrous oxide concentrations have increased significantly from pre-industrial values as well. Together, the combined radiative forcing<sup>2</sup> from these three greenhouse gases is +2.3 Watts per square meter ( $\text{W m}^{-2}$ ), relative to 1750, which dominates the total net anthropogenic forcing (+1.6  $\text{W m}^{-2}$ ). The total net anthropogenic forcing includes contributions from aerosols (a negative forcing) and several other sources, such as tropospheric ozone and halocarbons.

Climate model simulations that account for such changes in forcings have now reliably shown that global surface warming of recent decades is a response to the increased concentrations of greenhouse gases and sulfate aerosols in the atmosphere. When the models are run without these forcing changes, the remaining natural forcings and intrinsic natural variability fail to capture the almost linear increase in global surface temperatures over the past 25 years or so. But when the anthropogenic forcings are included, the models simulate the observed global temperature record with impressive fidelity (*Figure 1*). Changes in solar irradiance since 1750 are estimated to have caused a radiative forcing of +0.12  $\text{W m}^{-2}$ , mainly in the first part of the 20<sup>th</sup> Century, and this cannot explain the recent warming. Prior to 1979 when direct observations of the sun from space began, changes in solar irradiance are more uncertain, but it is well established that the sun has not caused warming since 1979. Moreover, the models indicate that volcanic and anthropogenic aerosols have offset some of the additional

---

<sup>2</sup> Radiative forcing is a measure of the influence that a factor has in altering the balance of incoming and outgoing energy in the Earth-atmosphere system and is an index of the importance of the factor as a potential climate change mechanism. Positive forcing tends to warm the surface while negative forcing tends to cool it.

warming that would have resulted from observed increases in greenhouse gas concentrations alone.



**FIGURE 1.** Comparison of observed continental- and global-scale changes in surface temperature with results simulated by climate models using natural and anthropogenic forcings. Decadal averages of observations are shown for the period 1906–2005 (black line) plotted against the center of the decade and relative to the corresponding average for 1901–1950. Lines are dashed where spatial coverage is less than 50%. Blue shaded bands show the 5–95% range for 19 simulations from 5 climate models using only the natural forcings due to solar activity and volcanoes. Red shaded bands show the 5–95% range for 58 simulations from 14 climate models using both natural and anthropogenic forcings. The figure is taken from the IPCC AR4 WGI Summary for Policymakers (2007).

A significant advancement since the TAR is that a larger number of simulations available from a broader range of models allows for a more definitive evaluation of the

role of various forcings in producing not only changes in global average temperature, but also changes in continental and ocean basin scale temperatures, sea level, and changes in extreme events such as frost days and heat waves. The patterns of warming over each continent except Antarctica and each ocean basin over the past 50 years, including greater warming over land than over the ocean, and their changes over time, are only simulated by models that include anthropogenic forcing (*Figure 1*). Attribution studies have also demonstrated that many of the observed changes in indicators of climate extremes consistent with warming, including the annual number of frost days, warm and cold days, and warm and cold nights, have likely occurred as a result of increased anthropogenic forcing. In other words, many of the recently observed changes in climate are now being simulated in models.

The ability of coupled climate models to simulate the temperature evolution on continental scales, and the detection of anthropogenic effects on each continent except Antarctica, provides even stronger evidence of human influence on the global climate than was available to the TAR. No climate model that has used natural forcing only has reproduced either the observed global mean warming trend or the continental mean warming trends. Attribution of temperature change on smaller than continental scales and over time scales of less than 50 years or so has not yet been established mainly because of the much larger natural variability on smaller scales.

Another powerful test of coupled climate models is their ability to simulate climate of the more distant past, such as conditions of the Last Glacial Maximum (order 20,000 years ago) and the relatively warm Mid-Holocene (5,000 years ago). While many aspects of these past climates remain uncertain, key features have been reproduced by climate

models using estimated surface conditions and radiative forcing for those periods. A substantial fraction of the reconstructed NH interdecadal temperature variability of the last 500 years, for instance, is very likely attributable to natural external forcing from changes in the sun and effects of volcanic events.

Such results increase our confidence in the observational record and our understanding of how temperature has changed. They also mean that the time histories of the important forcings are reasonably known (for instance, Beryllium isotope measurements can be used to estimate long-term changes in solar output through changes in cosmic radiation) and that the processes being simulated models are adequate enough to make the models very valuable tools.

### **How will future global temperatures be affected by greenhouse gas emissions from human activity?**

The ability of climate models to simulate the past climate record gives us increased confidence in their ability to simulate the future. We can now look back at projections from earlier IPCC assessments and see that the observed rate of global warming since 1990 (about 0.2°C per decade) is within the projected range (0.15°C– 0.30°C per decade). Moreover, the attribution of the recent climate change to increased concentrations of greenhouse gases in the atmosphere has direct implications for the future. Because of the long lifetime of carbon dioxide and the slow equilibration of the oceans, there is a substantial future commitment to further global climate change even in the absence of further emissions of greenhouse gases into the atmosphere. Several of the coupled model experiments performed by modeling groups around the world for the IPCC AR4 explored



the concept of climate change commitment. For instance, if concentrations of greenhouse gases were held constant at year 2000 levels (implying a very large reduction in emissions), how much more warming would occur due to the greenhouse gases already in the atmosphere? Such committed climate change is due to: (1) the long lifetime of carbon dioxide and other greenhouse gases; and (2) the long time it takes for warmth to penetrate into the oceans. Under the aforementioned scenario, a further warming trend would occur over the next 20 years at a rate of about 0.1°C per decade, with a smaller warming rate continuing after that. The associated sea level rise commitment is much longer term, due to the effects of thermal expansion on sea level. Water has the physical property of expanding as it heats up; therefore, as the warming penetrates deeper into the ocean, an ever increasing volume of water expands and contributes to ongoing sea level rise. Since it would take centuries for the entire volume of the ocean to warm in response to the effects of the greenhouse gases we have already put into the air, we are now committed to further sea level rise that would continue for centuries. Further glacial melt is also likely.

The 16 climate modeling groups (from 11 countries, including the U.S.) contributing to the AR4 produced the most extensive internationally coordinated climate change analysis ever performed. In total, 23 global coupled climate models were used to perform simulations of the 20<sup>th</sup> Century climate (described under the previous question), three scenarios of the 21<sup>st</sup> Century (based on low, medium and high emission scenarios), and three idealized stabilization experiments. In addition there were idealized carbon dioxide increase experiments, and associated stabilization experiments with doubled and quadrupled carbon dioxide amounts. These data were then collected, archived and made openly available for analysis at the DOE-sponsored Program for Climate Model

Diagnosis and Intercomparison (PCMDI) at Lawrence Livermore National Lab (LLNL) in Livermore, CA. Almost 1,000 scientists have accessed these model data, resulting in many papers assessed in the AR4. The outcome of this massive effort is much more extensive analysis, increased certainty of the most robust climate responses across different models, and much better quantification of best estimates and uncertainty ranges of projected warming for different emission scenarios. Moreover, the large model ensemble also provides for better quantification of regional climate change, extremes, climate change commitment, ocean circulation changes, and both near term and longer term climate change in response to future changes in radiative forcing.

Some of the major results include:

- Over the next two decades, all models produce similar warming trends in global surface temperatures, regardless of the scenario. The rate of the projected warming is near 0.2°C per decade, or about twice that of the “commitment” runs.
- Decadal-average warming over each inhabited continent by 2030 is insensitive to the emission scenario; moreover, the temperature change is very likely to exceed the model generated natural temperature variability by at least a factor of two.
- By the middle of the 21<sup>st</sup> Century the choice of scenario becomes more important for the magnitude of surface warming, and by the end of the 21<sup>st</sup> Century there are clear consequences for which scenario is followed. The best estimate of the global surface temperature change from today to the end of the century is +1.8°C (with a likely range of +1.1°C to +2.9°C) for the low emission scenario (B1, corresponding to a carbon dioxide equivalent concentration of 600 ppm by 2100) and +4.0°C (+2.4°C to +6.4°C) for the highest emission scenario (A1F1, corresponding to 1,550 ppm).

- Geographical patterns of warming show greatest temperature increases at high northern latitudes and over land, with less warming over the southern oceans and North Atlantic, as has been observed in recent decades. In spite of a slowdown of the meridional overturning circulation and changes in the Gulf Stream in the ocean across models, there is still warming over the North Atlantic and Europe due to the overwhelming effects of the increased concentrations of greenhouse gases.

- Snow cover is projected to contract. Widespread increases in thaw depth are projected over most permafrost regions.

- Sea ice coverage is projected to shrink in polar regions. In some projections, Arctic late-summer sea disappears almost entirely by the latter part of the 21<sup>st</sup> Century.

- It is very likely that hot extremes, heat waves, and heavy precipitation events will continue to become more frequent.

- Projections of sea level rise by the end of the century are similar to previous estimates, ranging from 30 to 40 cm, but do not include possible ice sheet collapse.

- About 60-70% of the projected sea level rise is due to thermal expansion of sea water. There is less certainty of the future contributions from other sources. For instance, the projections include a contribution due to increased ice flow from Greenland and Antarctica at the rates observed over the past decade, but how these flow rates might change in the future is not known.

- Increases in the amount of precipitation are very likely in high-latitudes, while decreases are likely in most subtropical land regions, continuing patterns observed in recent trends.

The climate models assessed in the AR4 have better and more complete representations of many physical processes. But as our knowledge of the different components of the climate system and their interactions increases, so does the complexity of climate models. Historical changes in land use and changes in the distribution of continental water due to dams and irrigation, for instance, need to be considered. Future projected land cover changes due to human land uses are also likely to significantly affect climate, especially locally, and these effects are only just now being included in climate models.

One of the major advances in climate modeling in recent years has been the introduction of coupled climate-carbon models. Climate change is expected to influence the capacities of the land and oceans to act as repositories for anthropogenic carbon dioxide, and hence provide a feedback to climate change. These models now allow us to assess the nature of this feedback. Though only relatively few global coupled climate models include the complex processes involved with modeling the carbon cycle, this feedback is positive (adding to more warming) in all models so far considered. Therefore, the addition of carbon cycle feedbacks increases the fraction of anthropogenic emissions that remain in the atmosphere, thereby giving higher values on the warm end of the uncertainty ranges.

## **Conclusions**

The scientific understanding of climate change is now sufficiently clear to show that climate change from global warming is already upon us. Climate models have greatly improved, increasing our confidence in the attribution of observed global warming to human activity and in the projections of future climate change. Uncertainties remain,

especially regarding how climate will change at regional and local scales. But the climate is changing and the uncertainties make the need for action all the more imperative. Mitigation actions taken now mainly have benefits 50 years and beyond now because of the huge inertia in the climate system. Therefore society will have to adapt to climate change, even if actions are taken to reduce the magnitude and rate of climate change. The projected rate of change exceeds anything seen in nature in the past 10,000 years and is apt to be disruptive in many ways, even if some changes may be benign or even beneficial in some locations and in the short-term. Hence it is critical to improve our scientific understanding of the climate impacts on scales and timeframes relevant for decision makers. It is also vital to plan to cope with the likely changes, such as enhanced droughts, heat waves and wild fires, and stronger downpours and risk of flooding. Managing water resources, for instance, will be major challenge in the future.

Again, it is an honor to have the opportunity to address the Subcommittee concerning the science of global climate change. I look forward to answering any questions.